Annual Project Summary

Study of a Potential Seismic Source Zone in South-Central Illinois

(Award Number 99HQGR0075)

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Program Element: (I) Products for Earthquake Loss Reduction
Microzonation mapping and Paleoliquefaction Study
(II) Research on Earthquake Occurrence and Effects
Investigation of Paleoseismicity

Key Words: Geologic Mapping, Liquefaction, Regional Seismic Hazards

Introduction

We report our progress based on the three proposed tasks in the original proposal. The first task is to examine the possibility of a complex tectonic structure as a potential seismic source in the area. The second task is to continue the ongoing paleoliquefaction studies in the region. The third task is to integrate the first two tasks in order to compare potential earthquake magnitudes with the extent of basement faults and the distribution of paleoliquefaction features.

Task 1: Study of Seismic Reflection Profiles

As part of this study, we have been collecting seismic reflection data from the petroleum industry as well as assessing seismic reflection data already in our possession (McBride and Kolata, 1999). One of the main structures in the study area is the Du Quoin Monocline and associated Centralia Fault Zone (Fig. 1). The north-trending Du Quoin Monocline separates the Fairfield sub-basin to the east from the Sparta Shelf to the west (Fig. 2). The Du Quoin Monocline underwent maximum uplift during Morrowan and Atokan time, but movements continued at least into Missourian time (early late Pennsylvanian) (Nelson, 1991, 1995). It is possible that subsequent movements have occurred, although this has not been confirmed

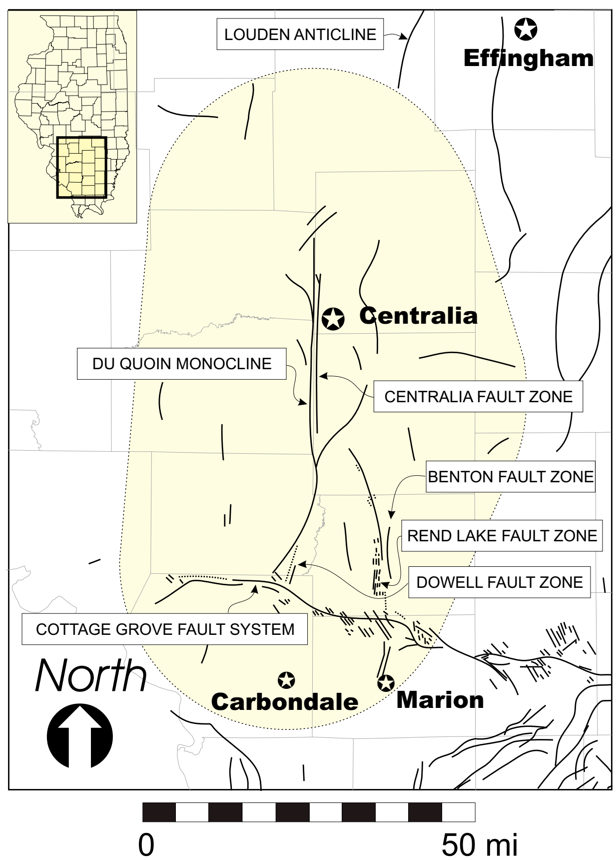

Figure 1: Major tectonic structures in south-central Illinois. The tectonic structures believed to be a potential seismic source zone is a complex structure that consists of Dowell Fault Zone, Du Quoin Monocline, and Centralia Fault Zone (Nelson, 1995).

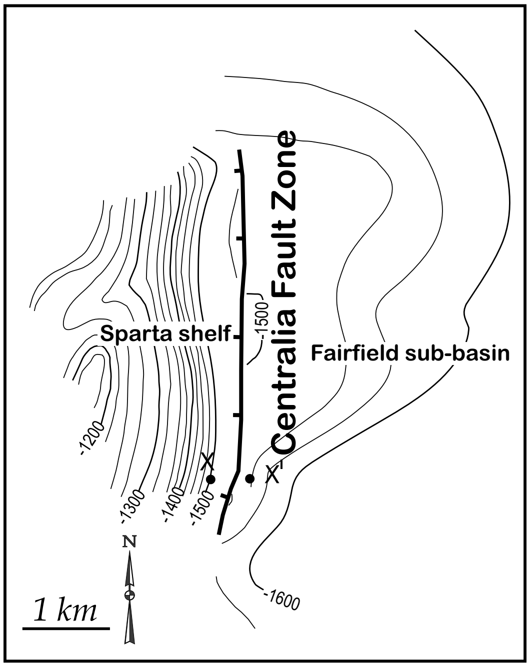

Figure 2: A structure-contour map of the Beech Creek Limestone (middle Chesterian), based on reflection data (using a 400-foot datum) over the Centralia Fault Zone (CFZ). The contour interval is 25 feet (~7.6 m). X-X' shows approximate location of the profile in Fig. 3a.

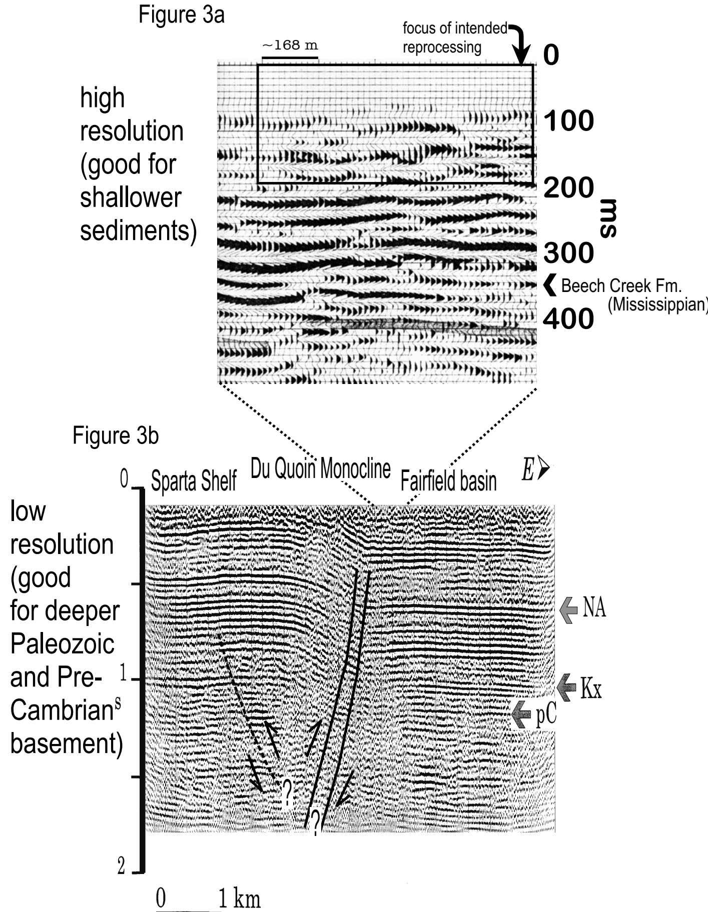

*Figure 3. (a) Small portion of high-resolution migrated from a seismic profile across the Centralia Fault Zone and east flank of the Du Quoin Monocline (Fig. 2). (b) Migrated seismic reflection profile across the southern Du Quoin Monocline showing steep faulting on limb of fold. **NA** is the base of the Upper Devoniam New Albany Shale, **Kx** is the base of the Ordovician-Cambrian Knox Supergroup, and **Pc** is the Precambrian reflector. Dominant reverse fault interpretation shown by solid lines and subordinate fault by dashes ("?" indicates uncertainty in our current interpretation).*

from drillhole data. A relatively low- resolution reflection profile over the unbranched part of the Du Quoin Monocline shows a strongly asymmetric monocline affecting all Paleozoic strata reflectors (Fig. 3b). The abrupt lower hinge implies a steep, west-dipping reverse fault in the Precambrian basement that facilitated folding of Paleozoic strata. Subtle reversals in the dip of Paleozoic reflectors west of the forward hinge of the monocline suggest a possible antithetic "backthrust." These faults are inferred to have penetrated Precambrian basement rocks and formed a major shear zone there.

Several short, high-resolution seismic lines across the southern Du Quoin Monocline (Fig. 3a) clearly image the monocline and the Centralia Fault Zone cutting the lower hinge of the fold. The fault is a clear-cut, west-dipping normal fault from upper Mississippian reflectors down through the deepest coherent reflectors, which are probably within the Knox Group (Lower Ordovician and Cambrian). The dip of the fault plane averages 70° to 75° and the throw is 30 to 50 m at all levels imaged. The seismic data agree with information from shallow drilling and observations in underground coal mines that drove tunnels across the Centralia Fault Zone (Nelson, 1995). As shown in Figure 2, the fault zone is composed of normal faults with the principal displacements down to the west. Hence, Centralia faults have throw opposite to uplift on the monocline, and represent extension rather than compression. They appear to indicate a period of reactivation of the structure in the lower Paleozoic and basement rocks. Structural contour maps (Fig. 2) indicate a significant tightening of the fold on the hanging wall of the fault, again with a convex-to-the-east pattern, which implies that the later normal faulting along the Centralia Fault Zone significantly modified the fold structure that originated from compression.

As Brownfield (1954) pointed out, the Du Quoin Monocline began to form near the end of the Mississippian Period and was largely complete by the time of deposition of the youngest Pennsylvanian marker beds preserved in the area, which are upper Missourian. In contrast, the Centralia Fault Zone displaces all Pennsylvanian layers with no upward loss of displacement. Brownfield, therefore, concluded that the faulting is post-Pennsylvanian and represents an episode of extension unrelated to the earlier east-west compression that formed the monocline. The Centralia Fault Zone likely connects at depth with the basement fault beneath the Du Quoin Monocline. This fault underwent two episodes of movement: reverse (west side up) during the Pennsylvanian, and normal (west side down) after the Pennsylvanian. We are currently negotiating with the owners of three high-resolution (i.e., 60-fold CDP data with a shot and receiver spacing of about 34 m, dynamite source) reflection profiles across and along the Centralia Fault Zone to receive copies of the digital data in order to extend the depth of investigation into the deep basement (i.e., from 1.2 to 2.0 s, two-way travel time) as well as into the shallow subsurface (upper 50-100 ms, Fig. 3). We have already negotiated a license to the data and possess paper copies of the data and shot point location maps.

In similar fashion, a zone of small, high-angle normal faults called the Rend Lake Fault Zone parallels the west flank of the Benton Anticline (Nelson, 1995) (Fig. 1). Structural mapping suggests that the folding took place mainly during late Mississippian and early Pennsylvanian time, whereas normal faulting was late- or post-Pennsylvanian (Keys and Nelson, 1980). A seismic profile, obtained from Mobil Oil Corp., northeast of the Benton Anticline and south of the King Anticline (Fig. 4) reveals very subtle anticlinal and monoclinal folding, previously unmapped, that corresponds to abrupt bends and breaks in reflectors (A, B; Fig. 4) along which high-angle faults are interpreted that facilitate folding higher in the section. The detection of offsets is more difficult beneath the base-of-Knox reflector, although abrupt terminations are visible

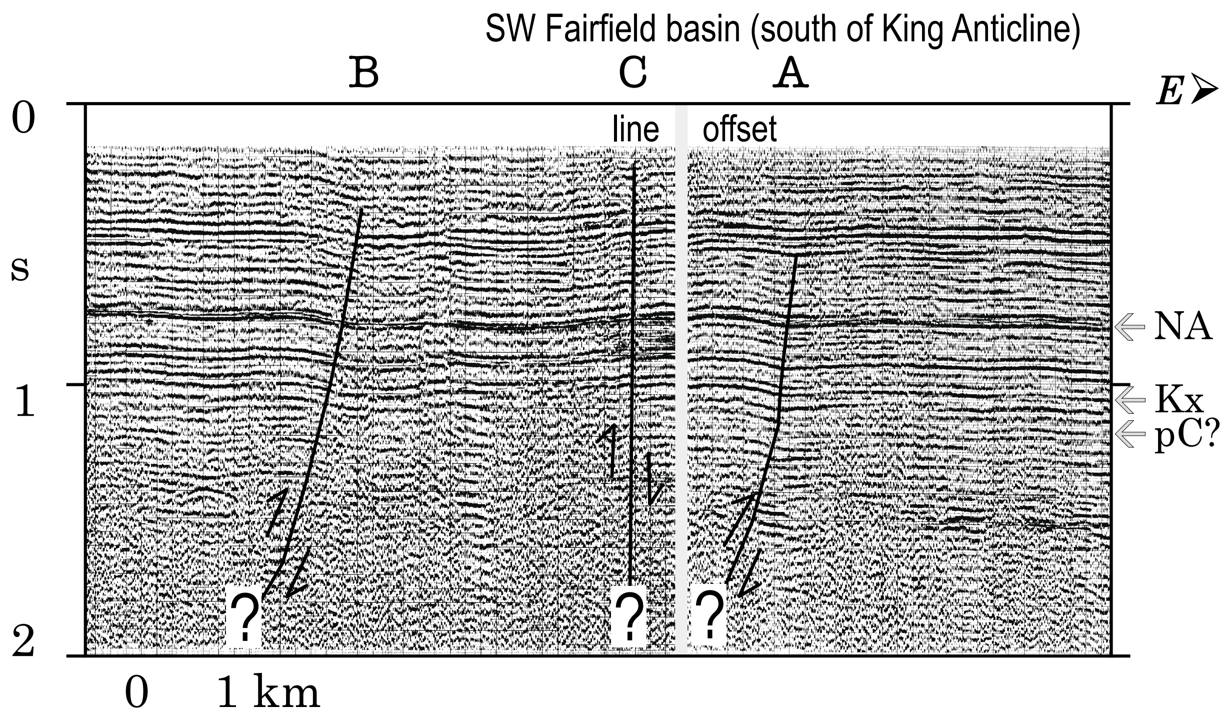

Figure 4. Stacked seismic reflection profile south of the King Anticline and northeast of the Benton Anticline (Fig. 1). Interpreted master reverse faults are marked with solid lines.

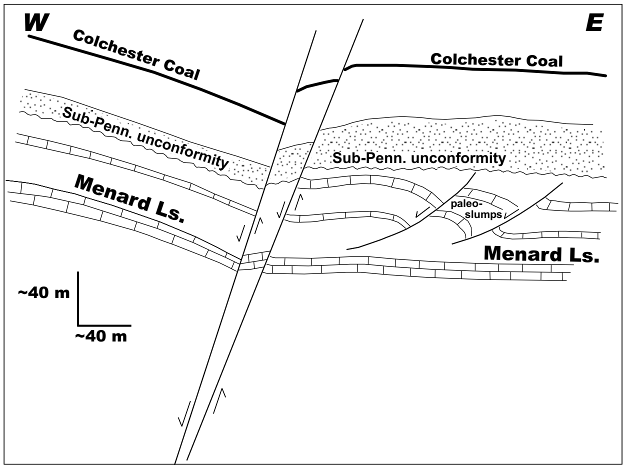

Figure 5. Interpretive cross-section based on bore-hole data across the Centralia Fault Zone near the profile in Figure 3a (McBride and Kolata, 1999).

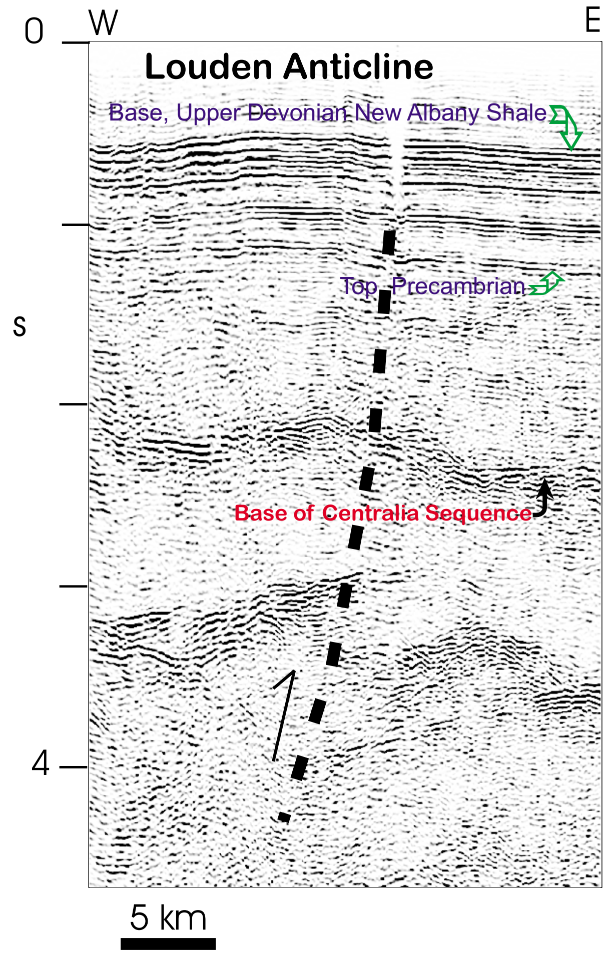

Figure 6. Recorrelated migrated vibroseis section over the Louden Anticline (Fig. 1). Thick dashed line gives interpretation of a major basement reverse fault that has been reactivated to facilitate the production of the fold within the Paleozoic sediments.

beneath fault A and abrupt bends occur on reflectors beneath fault B (Fig. 4). A likely vertical fault appears below point C along the profile (Fig. 4). These faults (especially A and B) appear to disrupt the uppermost basement reflectors. The derived pattern of lower Paleozoic and basement faults is consistent with the direction of fold vergence inferred from the asymmetry of folding, in this case an east vergence. The pattern of basement-penetrating faulting in and near the Rend Lake Fault Zone probably is a product of the same post-Pennsylvanian, east-west extensional stress regime that created the Centralia Fault Zone.

Detailed analysis of well records in the area of the seismic profile (McBride and Kolata, 1999) across the Centralia Fault Zone (Fig. 5) yields additional insight into the history of faulting (McBride and Nelson, 1999). A number of drill holes penetrated fault surfaces, indicated by missing section. A seeming anomaly is that there is little or no apparent displacement of the Menard Limestone (Chesterian; upper Mississippian), whereas the Colchester Coal (middle Pennsylvanian) is downthrown 35 to 45 m to the west. The interval of strata between the Menard and the Colchester thickens by a comparable amount (35-45 m) on the eastern, currently *upthrown*, side of the fault zone. Specifically, a thicker interval of upper Chesterian rocks (above the Menard) is preserved beneath the sub-Pennsylvanian unconformity on the east side of the fault zone (Fig. 5). In several wells, these strata are jumbled out of normal order, suggestive of large-scale paleo-slumping. Also, basal Pennsylvanian (Morrowan) rocks thicken abruptly on the east side of the fault zone and contain much thicker, more massive sandstone units than those found west of the zone. The conclusion is that during latest Mississippian and early Pennsylvanian (Morrowan) time, the west side of the Centralia Fault Zone was uplifted as a reverse fault, concurrent with folding of the Du Quoin Monocline. Earth movements triggered landslides of weakly lithified Chesterian sediments. Further uplift of the west side, and downwarping of the east side, allowed a thicker succession of sediments to accumulate east of the fault zone. The later reactivation of the fault zone as a normal fault restored the Menard Limestone to nearly its pre-faulting position during the late Pennsylvanian or Permian, displacing middle Pennsylvanian rocks 35 to 45 meters down to the west.

We have obtained digital vibroseis reflection data over the Louden Anticline, which is located just to the northeast of the Du Quoin Monocline (Fig. 1), and applied the technique of "extended re-correlation" (Okaya and Jarchow, 1989) to extend the recording time from just a few seconds to several seconds. Our results (Fig. 6) indicate an interpreted major deep basement fault zone that projects from an estimated equivalent depth of at least 12 km up to the forward hinge point of the east-facing flexure of the monoclinal limb. The observed length of the axial trace for the Louden Anticline of 30 km (Nelson, 1995) and a basement penetration over a vertical length of 9 km (i.e., 3 s @ 6000 m/s) yields a fault surface area of 270 km^2.

We are also in the process of negotiating with the Pharis Petroleum Company (seismic data owners) in order to obtain additional high-quality digital data for which we have already received a license to use the paper sections for research purposes. We are also awaiting decisions from other data owners (Vastar Resources, and Seitel, Inc.) on our proposals to obtain additional seismic reflection data.

Task 2: Paleoliquefaction Study

Most of the existing data on paleoliquefaction features in the vicinity of the study area in southern Illinois (Figure 7) have been compiled. We are in a process of constructing a set of GIS maps showing the locations of the paleoliquefaction features with layers of other important geological information, such as the types of surficial materials, drift thicknesses, and material properties. The maps will be a part of the deliverable with our final report. The maps will be also published on the Illinois State Geological Survey's web pages. This mapping task will be a collaborative effort by several research teams, including (1) Dr. Mike Wiant and Dr. Ed Hajic of the Illinois State Museum (ISM) - The ISM team has conducted a three-year reconnaissance search of paleoliquefaction features in part of our project area (funded by the NEHRP); (2) Dr. Steve Obermeier (formerly with the USGS) who has been carrying on a continuous investigation of paleoliquefaction dikes in Illinois since 1990; and (3) Dr. M. Tuttle of the University of Maryland who is conducting a paleoliquefaction study in the East St. Louis area, including Shoal and Silver Creeks which are in the western part of our study area.

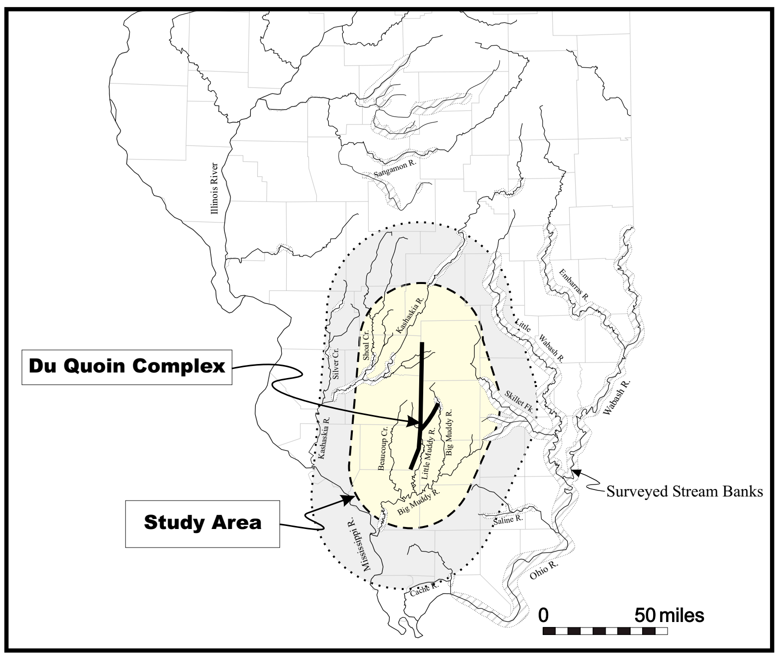

Figure 7: The study area is centered around the Du Quoin Complex in south-central Illinois. The area is selected because the Complex has structural characteristics of a potential seismic source zone; the area has not been adequately surveyed for paleoliquefaction features; and the area is covered by a network of seismic reflection profiles recently released to the Illinois State Geological Survey.

For field reconnaissance, we have examined the existing map information in Soller (1998) and Berg and Kempton (1987) for selecting potential sites where thick unconsolidated alluvium would have had a high potential for liquefaction during an earthquake. A layer of loose, clean, medium-grained sand deposit, underlying a clay/silt layer, is typical the sites where liquefaction features are found. Several high potential sites were identified through studying the map information. We are focusing our field work on searching for paleoliquefaction features along the Big Muddy River, Little Muddy River, Beaucoup Creek, and Crooked Creek.

We have also completed the design and manufacturing of an in-house device to measure shear wave velocities of surficial materials during our site-specific study. This device, called the "Geoprobe Geophone System (GGS)," is built by using an existing Geoprobe and seismograph. Our system is similar to that of the seismic cone penetration test (Campanella et al., 1986). Geoprobe Geophone System was developed by combining three existing pieces of equipment at the ISGS: a geophone assemblage, a Geoprobe machine and a seismograph. The set up of this system, is shown in Figures 8 and 9. The geophone assemblage is made with three geophones (two orthogonal horizontal and one vertical) set into a Geoprobe sampler. Two models of geophones will be used. Both geophones are made by the Geo Space Corporation of Houston, Texas. One is the model GS- 20DM, which has a natural frequency of 10 Hz with a dimension of 1.04" x 0.875". The other is the miniature model GS-14-L3, which has a natural frequency of 28 Hz with a smaller dimension of 0.68" x 0.66". The smaller dimension may be desirable for deeper testing because we can assemble them into a driven sampler of smaller diameter. This three-geophone assemblage will allow us to measure both shear and compressive wave velocities. The Geoprobe machine uses a hydraulic hammer to drive a sampler into the soils. A 12-channel Geometrics StrataView seismograph will be used for recording the wave velocities.

Both down-hole shear and compressive wave velocities will be measured with the three-component geophone assemblage, which will be driven down into the soils at each recording depth. The arrival time and waveform of energy produced by a horizontally polarized shear wave source at the surface will be recorded using a digital seismograph. Records will be obtained with two opposing surface source orientations at each downhole location, in order to ensure accurate interpretation of the onset of polarized shear wave motion.

A shear wave signal source is generated by a rigid beam, or a wooden post that is steel jacketed, coupled to the ground surface by the weight of a truck. The beam or wooden post must be securely coupled to the ground so that energy losses from plastic deformation of the soil beneath the beam or wooden post are minimized. The beam or wooden post is then struck horizontally by a horizontally pivoted wooden battering ram

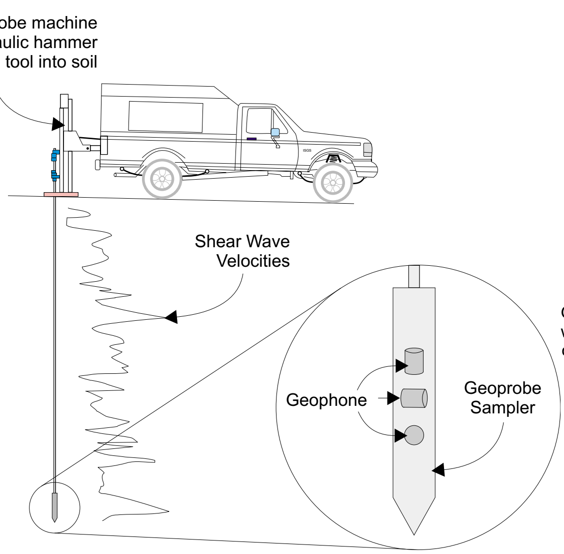

Figure 8: Truck-mounted geoprobe machine with a hydraulic hammer and the geophone assemblage.

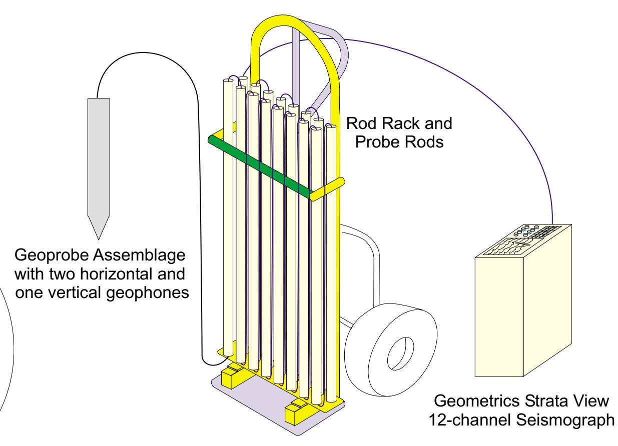

Figure 9: GGS: Geophone assemblage, probe rods and a 12-channel Geometrics StrataView Seismograph..

or by a large sledgehammer (Figure 10). The seismic signal source is usually placed with ends equidistant, within approximately 2-3 m, of the vertical Geoprobe hole. Seismic wave velocity estimates will be determined, running least-squares fits of travel times over a specific vertical distance at the detailed study sites.

This device will enable us to measure both shear and compressive wave velocities of the surficial materials to a depth of 30 meters or to the bedrock surface. The shear wave velocities are needed for numerical analyses using the SHAKE91 program. The results of the analyses would allow us to estimate the possible liquefaction mechanism during the past earthquake. The results may also help us gain an understanding toward the possible magnitude of the earthquake that induced the liquefaction.

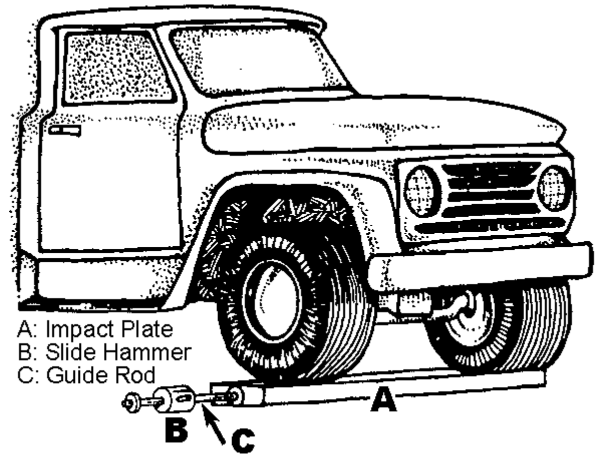

Figure 10: Set up of a seismic source for measuring shear wave velocities.

Results of the seismic wave velocities, geological setting of the detailed study sites, and numerical analyses are the major components for Task 3. These results will be a part of our deliverables in the final project report. The results will also be used for the ongoing regional microzonation mapping project of the CUSEC (Central United State Earthquake Consortium) State Geologists.

Task 3: Integration of Seismic Analysis and Paleoliquefaction Study

Integration of the results from the above two tasks will allow us to gain a new insight toward the paleoseismicity implication of the region. The length and depth of the fault(s) could be used to estimate the magnitudes of potential earthquakes. The information on fault parameters and the estimated potential earthquake magnitude will enable us to select and scale existing earthquake strong motion spectra for numerical analyses of liquefaction features. We are using the existing borehole data, Stack-unit map (Berg and Kempton, 1988), and Glacial drift thickness map (Piskin and Bergstrom, 1975) to set up geological models. Using the shear wave velocities obtained from the Task 2, we will use SHAKE91 to perform liquefaction analyses. Our intention is to investigate whether, based on the combination of earthquake location, estimated magnitude and local geological setting, the observed paleoliquefaction could be induced. So far only two sites have been selected for this task. One site is near the confluence of the Shoal Creek and Kaskaskia River in Clinton County, Illinois where a large 0.45-m wide and several smaller clastic dikes were discovered (McNulty and Obermeier, 1999). The other site is along the Big Muddy River in Jackson County, Illinois where several medium size clastic dikes were discovered by Dr. M. Tuttle. A few more sites will also be selected for detailed study after the completion of Task 2.

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Non-technical Summary

Seismic reflection data have been acquired from the petroleum industry and other sources for an area surrounding the Du Quoin Monocline and the Centralia Fault Zone complex, which is a candidate structure for governing earthquake locations in south-central Illinois. Locations of sub-surface faults from the reflection data will be compared with information now being assembled on paleoliquefaction sites in the study area. The comparison will be used to constrain possible magnitudes of paleo-earthquakes based on (1) area of observed or inferred sub-surface faults and (2) the distribution of paleoliquefaction patterns around the Du Quoin Monocline and the Centralia Fault Zone complex.